Shockless Explosion Combustion

– An Innovative Way of Efficient Constant Volume Combustion in Gas Turbines –

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This is an Accepted Manuscript of an article published by Taylor & Francis in Combustion Science and Technology on 30 Sep 2014, available online: `http://www.tandfonline.com/doi/full/10.1080/00102202.2014.935624`.

Abstract

Constant volume combustion (CVC) in gas turbines is a promising way to achieve a step change in the efficiency of such systems. The most widely investigated technique to implement CVC in gas turbine systems is pulsed detonation combustion (PDC). Unfortunately, the PDC is associated with several disadvantages, such as sharp pressure transitions, entropy generation due to shock waves, and exergy losses due to kinetic energy. This work proposes a new way to implement CVC in a gas turbine combustion system: shockless explosion combustion (SEC). This technique utilizes acoustic waves inside the combustor to fill and purge the combustion tube. The combustion itself is controlled via the ignition delay time of the fuel-air mixture. By adjusting the ignition delay in a way such that the entire fuel-air volume undergoes homogeneous auto-ignition, no shock waves occur. Accordingly, the losses associated with a detonation wave are not present in the proposed system. Instead, a smooth pressure rise is created due to the heat release of the homogeneous combustion. The current paper explains the SEC process in detail, and presents the identified challenges. Solutions to these challenges and the numerical and experimental approach are presented subsequently alongside with first preliminary results of the numerical studies.

1 Introduction

The idea of a gas turbine goes back to the year 1791. John Barber claimed a patent (**?**) in which he basically describes the idea and function of a gas turbine. Unfortunately, no materials fulfilling the thermophysical requirements were available at that time. In the first years of the 20th century, different people worked on the field of gas turbine systems. In 1903 Jens William Ægidius Elling invented a compressor with an efficiency between 85 % and 87 % that allowed the construction of the first gas turbine producing net power. The first constant volume combustion gas turbine was invented by Hans Holzwarth (**?**) in the year 1905. The constant volume combustion in closed vessels created the necessary pressure for the turbine; thus, no compressor was needed. The efficiency of this gas turbine was around 13 %. Due to the fast efficiency increase of the compressors and the lower complexity of a constant pressure combustion system, the constant volume combustion was replaced by constant pressure combustion gas turbines in the following years.

Better materials, turbine blade cooling, more efficient airfoils in the compressor and turbine, and higher pressure ratios led the way to more and more efficient gas turbines. These developments resulted in an efficiency of around 40 % for single cycle application and slightly above 60 % for combined cycle operation including the additional steam cycle. However, the idea of a non-steady combustion process remained in the focus of the scientific community. Pulsed combustion was associated with a higher efficiency, less emissions, and, due to the non-implicit need of a compressor or turbine for thrust generation, a very simple setup. During the 1940s, the first pulsejet engine was used for thrust generation. This engine only consisted of a tube with one-way valves to control the inflow, a fuel injection, and a spark plug. Later on, valveless pulsejet concepts were invented and investigated. Nevertheless, these devices had a poor fuel efficiency and very high emissions, mainly due to their lack of controllability as self-controlling systems.

The expected increase in efficiency is still one of the main advantages of such systems (**?**, **?**, **?**, **?**, **?**). Heiser and Pratt published a thermodynamic cycle analysis regarding the constant pressure (CPC), constant volume (CVC), and pulsed detonation combustion (PDC) in 2002 (**?**) for both the ideal and the real cycles. They conclude that the ideal PDC-cycle has a thermal cycle efficiency between 40 % and 80 % depending on the temperature ratio across the compressor. This increase in thermal efficiency makes constant volume combustion, in the mentioned study in the form of a PDC, very desirable for the gas turbine community. Unfortunately, this thermodynamic cycle is difficult to achieve in practice. Several types of pressure gain combustors, suitable for a gas turbine system, were proposed and investigated in the last decades. Pulse combustors, pulse detonation engines, rotating detonation engines, and wave rotors are the main types of these devices.

Pulsed combustors were the first proposed technique to realize a pressure gain combustion. Beginning in the 1940s until today, several papers have been published describing and investigating different ways of pulsed pressure gain combustion (e.g., (**?**, **?**, **?**, **?**, **?**, **?**, **?**)). Putnam et al. (**?**) published an overview on the work of several research groups on pulsed combustors in 1986. However, even though these systems provide a pressure gain in the combustion chamber, they can not be considered as constant volume combustion since in most of these devices a deflagration wave is responsible for the chemical reaction and the combustors are open to the downstream side.

An overview on the PDC was published in 2004 by Roy et al. (**?**) and Wolański published an overview on the detonative propulsion in 2013 (**?**). In a pulsed detonation combustor a fast traveling detonation wave is responsible for the combustion of a fuel-air mixture. Due to the very high velocity of the detonation wave (e.g., around 2000 m/s for hydrogen-air flames), the mixture is burnt quasi-instantaneously and the volume of the mixture does not change during the combustion process. However, the detonation wave is also responsible for drawbacks of this combustion system. First of all, the flame front needs space to gain the speed of a detonation wave in the so-called deflagration to detonation transition process (DDT). In this volume the combustion is not fast enough to be considered as constant volume combustion. Secondly, the detonation wave implies a very strong and sharp pressure peak, which is harmful to the turbine and other parts of the engine. Lastly, the detonation wave is accompanied by moving flow trailing the wave. The according kinetic energy may not be fully converted to technical work by the turbine and, thus, is lost.

In order to partly bypass the mentioned losses, the rotating detonation engine was suggested. Lu et al. (**?**) published a work on the challenges, models, and engine concepts in 2011. In this type of engine, a continuous detonation wave is traveling through an annular chamber. The fresh fuel-air mixture is constantly injected into the combustion chamber to feed the rotating detonation. This supply of the fresh mixture presents the main problem of these devices. Depending on the radius of the annular chamber and the speed of the detonation wave, this supply requires to be injected in a very short time. However, since these devices still employ a detonation wave implying a shock wave in the combustion chamber, the shock induced losses are still existing. In addition, the shock wave is constantly traveling around the combustion chamber and, thus, into the turbine inlet where significant problems regarding cooling may occur.

In 2006 Akbari et al. (**?**) published an extensive review on the wave rotor technology and its applications including an overview on the historical development of this technique. The wave rotor technology allows to create a real mechanically closed chamber to realize constant volume combustion. In these devices no detonation and accordingly no shock is present, which removes most of the potential losses described for the PDC-systems. The main problem of these devices is found on the mechanical side. The wave rotor consists of a moving barrel of tubes that needs to be sealed on both ends during the combustion process. This seal is difficult to realize in a practical gas turbine system especially regarding the lifetime and maintenance intervals of existing gas turbine systems. Additionally, the cooling of this barrel is a challenging task.

Accordingly the optimal pressure gain combustion system needs to fulfill the following points:

1. constant volume combustion,
2. without shock waves and their induced losses,
3. no moving parts in the main air path.

The proposed shockless explosion combustion process (SEC) uses several physical properties of the fuel-air mixture to get close to this optimal pressure gain combustion. The remainder of the paper is organized as follows. The combustion process and the advantages of the SEC process will be described, followed by the numerical approach, as well as the related challenges and some preliminary results.

2 Combustion Process

Similar to pulsed detonation combustion, the shockless explosion combustion process (SEC) is based on a cyclic combustion process. The main phases of the shockless explosion combustor are shown in figure 1.

[Fig. 1 about here.]

The SEC cycle is based on four different stages. A standing pressure wave is established inside the combustion tube. The moment when this pressure wave reduces the pressure at the tube inlet below the plenum pressure, the tube is filled with compressor air. After filling a volume with pure air, fuel is added to the combustion air until around 40% of the tube is filled with a combustible mixture. The air volume is needed to separate the hot flue gases from the previous cycle and the fresh fuel-air mixture. Due to the hot air from the compressor, the mixture undergoes auto-ignition. The equivalence ratio inside the combustion chamber is adjusted in a way that the ignition delay matches the residence time of the mixture in the tube. Thus, the entire fuel-air volume undergoes homogeneous auto-ignition and the mixture is burnt completely and instantaneously, leading to a significant, but smooth, pressure increase without any shock waves. In addition, the ignition delay is adjusted to match the oscillation period. This means that the combustion of the mixture occurs simultaneously with the pressure wave raising the pressure at the tube inlet. The pressure wave is amplified and travels to the end of the combustion tube where it is reflected as a suction wave which restarts the process. Since this process must be coupled to the acoustic resonance of the combustion tube, the firing frequency will be around 250 Hz for a tube length of around 80 cm. Beside these values, a simple calculation of the process provides an idea of the expected power density of such a combustion tube burning dimethyl ether at a pressure of 30 bar. These parameters are shown in table 1.

[Table 1 about here.]

From the operational point of view, the turndown and part-load of the device are crucial operating conditions. In order to realize a part-load two possible ways exist. First, it is possible to lower the mean equivalence ratio per charge. This will result in a lower combustion temperature and thus will decrease the firing frequency. The second option is to reduce the volume of the fresh fuel-air charge. By doing so, the combustion temperature will remain the same and the firing frequency will not change. The according changes in the static pressure downstream of the combustion tube are not fully determined yet and are part of the ongoing research project. However, the proposed process cycle implies several advantages in comparison to pulsed detonation combustion, which are most likely to result in an overall efficiency increase.

1. Smooth pressure rises

In contrast to pulsed detonation combustion, no detonation waves are employed in the SEC-cycle, because the SEC only results in a smooth rise of pressure. These smooth pressure changes are less harmful for the machine, allow for a smaller plenum downstream of the combustor, and are not associated with losses.

2. No exergy losses

The detonation wave in a PDC is accompanied with a significant amount of kinetic energy, which is introduced by the detonation wave. Unfortunately, this kinetic energy is most likely lost in the process since it is difficult to convert this energy to mechanical work in the turbine. In addition, parts of the kinetic energy will be dissipated in the plenum downstream of the combustor. The shockless explosion combustor will not induce as much kinetic energy. Thus, the exergy losses associated with the kinetic energy behind the detonation wave are not present in the SEC.

3. No DDT-losses

Since a direct ignition of a detonation is extremely energy consuming, pulsed detonation combustors are most likely to employ a deflagration to detonation transition. In order to achieve this transition, at least a small distance is needed which is directly associated to losses because no constant volume combustion is achieved in this region. For the SEC, these losses do not exist due to the homogeneous auto-ignition that does not require any developing distance.

4. Mechanical integrity

The proposed system mainly consists of a steady tube without any moving parts or internal obstacles (for flame acceleration). Therefore, it is easy to realize the cooling of the combustion chamber and to integrate such a device in a gas turbine system. No seals against moving parts are necessary and no obstacles inside the combustor require cooling. This ensures a high lifetime and long maintenance intervals for such a system.

According to these advantages, the proposed process is an improvement to the existing pressure gain combustion cycles. The lack of a shock wave not only reduces the losses of the combustion system but also removes some of the mechanical problems regarding the turbine or sealing of such a system. The homogeneous auto-ignition creates a real constant volume combustion including a significant pressure gain in the combustion tube. Finally, the lack of moving parts in the combustor increases the reliability and lifetime of the proposed system.

To overcome the challenges of the proposed SEC cycle, the planned experiments are based on and supported by numerical simulations, which will set the sensitivity limits, calculate the needed fuel-air mixtures, and yield a more detailed insight into the combustion process. The numerical approach to gain these data is shown in the following section.

3 Simulation

In order to approximate constant volume combustion within the combustion tube, the chemical reaction must be as homogeneous as possible. The only means of ignition such that the entire volume of gas ignites homogeneously (i.e., not at single hot-spots) is auto-ignition. Precise control over the ignition delay times, despite residual exhaust gases, pressure waves, and other perturbations is therefore required. Optimization toward this aim poses several challenges and can not be achieved by experiments alone.

A fast simulation code is necessary to perform parametric studies on the process. To this end, a simplified model system has been employed: By only considering radial symmetric flows, the simulation has been reduced to one spatial dimension. The Navier-Stokes equations reduce to the computationally much cheaper Euler equations if viscosity is neglected. This approximation is common for the simulation of gaseous flows. At a later stage of the project, the full equations will be considered. The equations are closed by the ideal equation of state, $p = \rho RT$. The thermodynamic behavior of each species is modeled using NASA polynomials, i.e., we consider both the gas constant $R = R(Y)$ and the internal energy $e = e(T,Y)$ to depend on the mass fractions Y.

Even with these simplifications, the simulation poses a computational challenge on its own. The reactive Euler equations require much computational effort when a high number of species is involved. Early investigations are based on heavily under-resolved computations to have acceptable computational costs. The knowledge gained will then be used for optimization with more sophisticated models.

The Euler equations are solved using a finite volume approach (FVM) for the gas dynamics and by including an external kinetics solver via strang operator splitting. The HLLE approximate Riemann solver (**?**) is being used. Second order reconstruction in time and space ensures that the overall simulation is close to second order accurate. The kinetics are handled by a specialized solver compatible with the format used by Flamemaster, a chemical kinetics package by Heinz Pitsch. The ideal gas law is also handled by the kinetics code, which allows for a possible extension to more general equations of state. The species' enthalpies of formation contribute to the internal energy e, coupling mass and energy flow. To avoid problems with this dependence, only the internal energy's difference to a common reference state, i.e., $e = h(T) - h(T_0) - RT$, is stored. The full energy term is then reconstructed within the kinetics solver.

For dimethyl ether, only single ignitions have been simulated to date using a reduced mechanism provided by L. Cai, RWTH Aachen University, based on a full mechanism by Pitsch/Peters, which has not been published yet. In figure 2 the calculated time histories are shown close to the open end of the tube for a typical ignition at machine conditions. More detailed simulations, including optimization towards the SEC case, require long simulation times but are in progress. Smaller models are expected to arise within the next months. Preliminary calculations with unphysical models of the expected size indicate that they will drastically speed up the simulation process.

[Fig. 2 about here.]

4 Challenges

Alongside all of the mentioned advantages, new challenges arise from the shockless explosion combustion concept. The first and most crucial challenge is the correct and reliable conditioning of the mixture. Since the fuel will be injected in the hot compressor air stream, fast and good mixing in the radial plane of the combustor is needed. Otherwise, premature ignition in one or more locations will occur and ignite the entire fuel-air mixture. In addition, the fuel flow must be controlled such that the ignition delay matches the residence time assuring homogeneous auto-ignition. Finally, the created fuel-air mixture must be separated from the hot walls of the combustion chamber and the hot exhaust gases of the previous cycle by inert air volumes to avoid ignition by the hot environment.

A test rig employing water as working fluid was created to assess these problems experimentally. Known from literature (e.g., (**?**, **?**)) the mixing of water with dye is a good indicator for the fuel-air mixing in combustion systems. Furthermore, the associated velocities and frequencies are reduced for the same REYNOLDS and STROUHAL numbers due to the different fluid properties of water. The ignition delay time must be precisely adjusted to assure homogeneous auto-ignition of the mixture. Challenging for this point is the fact that the ignition delay time depends not only on the equivalence ratio but also on several other parameters such as temperature, pressure, and fuel composition.

However, from a theoretical perspective, the ideal charge for the model case of a single ignition is obvious: Given a constant flow velocity u and ignition delay times of the fuel mixture as a function $\tau(T,\phi)$, ϕ must be adjusted on injection such that $\tau(T,\phi) = t_{\text{ign}} - t$, which results in the combustor being filled up to ut_{ign} upon ignition. It is practical to keep T constant and only vary ϕ. As mentioned above, additional perturbations must be taken into account for the real SEC process:

The entire process is based on acoustic modes oscillating through the tube. The main pressure wave present prior to ignition is a low pressure wave being reflected from the exhaust. If it hits the mixture before ignition, it will change its temperature and therefore influence the ignition time, resulting in an inhomogeneous explosion. Solid estimates of the strength and time of such events are needed to achieve accurate predictions. Further potential sources of perturbation are residuals of burnt, hot gas which may mix with the fuel and heat flux from the walls of the combustor. Their effects are to be evaluated and must also be considered in the control strategy. The aim is to estimate the strength of these effects. At a later stage necessary strategies and sharp estimates will be developed in more detailed simulations.

The high sensitivities in the mixing process rule out most standard fuels for the early stages of the project. To minimize the number of variables that must be controlled within the process, fuels for the SEC process will be tailored to match the desired ignition delay times over a wide range of possible temperatures and pressures, leaving only the fuel/air equivalence ratio as a variable for which stringent control is required. This will be achieved by making use of the negative temperature coefficient (NTC) behavior of certain fuels. NTC-regions are temperature intervals for which the ignition delay time increases with temperature. By mixing a fuel with pronounced NTC behavior and one without a NTC region, the temperature dependency can be removed within a range of about 200 K, which would potentially suffice to neglect the oncoming waves completely. The risk of detonation waves due to premature ignition can be reduced by using fuels whose excitation time is of similar order as the ignition delay time. When hot spots occur the excitation time determines the propagation speed of the reaction in the mixture. Thus, if the ratio between the ignition delay time and the excitation time is close to unity, auto-ignition of the surrounding mixture occurs before any detonation cells can develop. The INSTITUT FÜR TECHNISCHE VERBRENNUNG at RWTH AACHEN UNIVERSITY investigates mixtures of fuels to achieve this (see for example (**?**)).

The second challenge is to achieve the desired firing frequency. To do so, very fast valves are needed to assure the correct filling of the combustion tube. No mechanical valve system that is capable of handling hot flows at such frequencies and, in addition, is reliable over a long operational period is known to the authors. Already in the early work of the pulsed combustors, this problem exists. Kentfield et al. (**?**) suggested a so called thrust-augmenter flow recifier setup in which the back flow due to the pressure gain was guided into a channel and transported to the downstream side of the combustion tube. In a similar way, valveless pulsejet engines are designed, where parts of the exhaust gases are guided through the inlet and additional ports into the environment. However, for the proposed SEC-process it is necessary that the pressure wave which is traveling upstream through the combustion tube is reflected similar to a reflection by a closed tube. Thus, the known bypass systems to create such a valveless system are not suitable for the SEC-process because the pressure wave is lost through these systems. Fluidic devices seem to be a promising technology to achieve such valve-like behavior without any moving parts. Fluidic Diodes are special geometries which have a low pressure loss in one direction and a high pressure loss in the other. A picture from the numerical simulation of such a device is shown in Fig.3.

[Fig. 3 about here.]

The air enters the system from the left around the center-body with a very low pressure loss. The combustion tube is connected on the right side of the picture. The combustion-driven pressure rise will increase the pressure in the combustion tube to a level higher than on the inflow side for a very short time. The exhaust gases, which are then trying to stream backwards (i.e., from right to left) through this device will face a very high flow resistance and the pressure wave will be reflected from the center-body to travel downstream into the combustion tube. Hence, a valve setup without any moving parts is used that creates the needed flow characteristics to sustain the unsteady combustion process.

5 Conclusion

The idea of constant volume combustion is promising for a step change in the efficiency of gas turbines. As shown by thermodynamic cycle analysis, the thermal efficiency can be increased to 40 % – 80 % for an ideal PDC cycle. Several ideas for the implementation of constant volume combustion in a gas turbine system exist. The most investigated technique is the pulsed detonation combustion that utilizes fast traveling detonation waves to approximate constant volume combustion. These detonation waves are associated with several disadvantages: high pressure peaks, exergy losses due to kinetic energy, and losses due to the shock wave. The proposed shockless explosion combustion overcomes these disadvantages by making use of traveling pressure waves inside the combustion chamber to trigger the process and homogeneous auto-ignition to create instantaneous combustion without harmful and entropy generating pressure peaks. In addition, the SEC is expected to reach even higher efficiencies than the PDC. Thus, the SEC is very promising for a step change in future gas turbine efficiency.

The main challenges were identified and first solutions were proposed. The work on these challenges from both the experimental and the numerical side are ongoing. In the near future, the technical feasibility of the theoretically predicted behavior will be investigated and assessed. The sensitivity of the process to perturbations in the ideal combustion cycle will be estimated.

Achnowledgements

Financial support from the German Science Foundation (DFG) as part of the Collaborative Research Center (SFB) 1029 “Turbin – Substantial efficiency increase in gas turbines through direct use of coupled unsteady combustion and flow dynamics” is gratefully acknowledged.

List of Figures

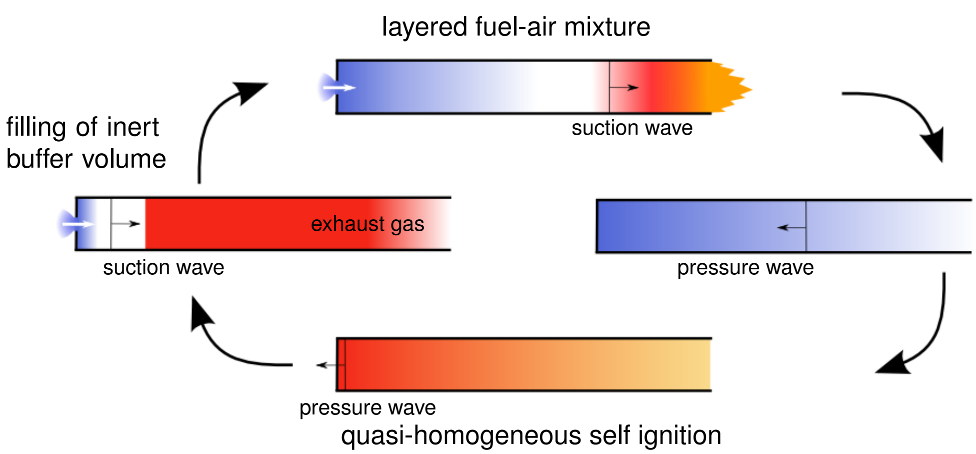

Fig. 1: Process cycle of the shockless explosion combustor (see the online version to view in color).

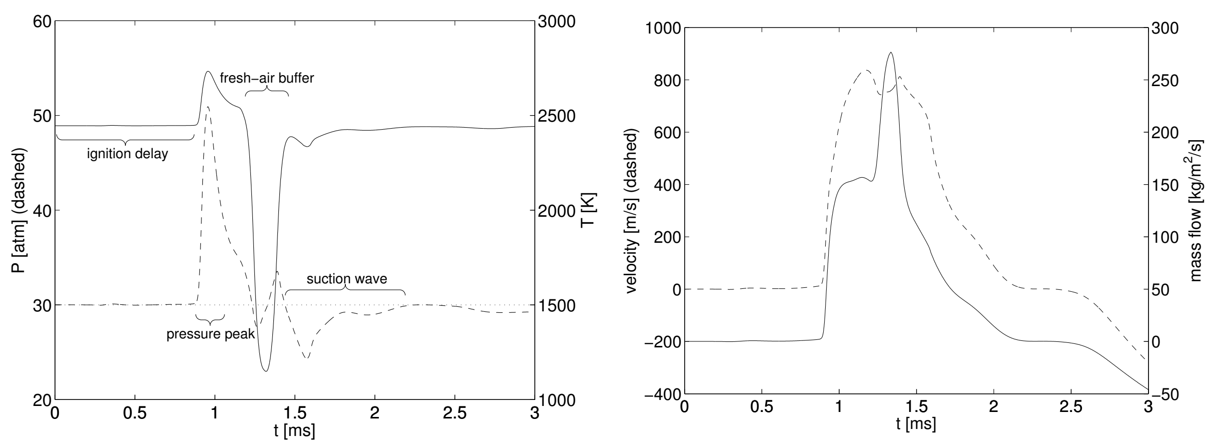

Fig. 2: Profiles close to the end of the pipe for a single ignition at machine conditions. Initially filled with 40 % DME/air at 1000 K and 30 atm and zero velocity. This is followed by a 10 % buffer volume of fresh air at 1000 K. The rest of the tube is filled with burned gas from an earlier cycle. The right end opens into a 30 atm plenum.

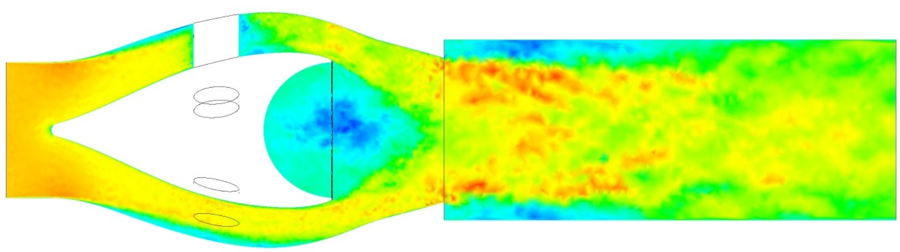

Fig. 3: Instantaneous velocity contour of a CFD-Simulation of the first design of the proposed fluidic diode (see the online version to view in color).

List of Tables

Table 1: Approximate operating parameters of one SEC-tube burning dimethyl ether at a pressure level of 30 bar.

length in mm	800	equivalence ratio	1
diameter in mm	40	average temperature in K	1700
filling ratio in %	0.4	frequency in Hz	258
intermediate air volume ratio	0.05	thermal power in MW	11